A NOVEL STANDARDIZED ASSESSMENT FOR THE NEW END USES OF RECYCLED WATER SCHEMES

By

Zhuo Chen

Submitted in fulfilment for the degree of

Doctor of Philosophy

Faculty of Engineering and Information Technology

University of Technology, Sydney

Australia

2014

CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Student: 陈亮

Date: 15/04/2014

ACKNOWLEDGEMENTS

I would like to take this opportunity to express my sincerest gratitude and admiration to my supervisors. Without their continuous guidance, care and support, this dissertation would not have been developed and accomplished perfectly. My deepest appreciation and heartfelt thanks goes to my principal supervisor, Prof. Huu Hao Ngo, for his respectable erudition, insightful guidance and invaluable advice at every stage of my PhD study. Not only he did steer me in the novel research direction, but also he cultivated, evolved and enhanced my professional, academic and personal growth. His spirit of persistence, dedication and passion deeply impressed me. I am also deeply grateful for my co-supervisor, Dr. Wenshan Guo, whose thoughtful guidance, constructive comments, revisions and inspirations, and warm encouragement were very important to the completion of this dissertation as well as relevant scientific papers.

This research work was funded by the Australian Research Council (ARC) Industry Linkage Grant (LP100100494). Besides, I am thankful to the University of Technology, Sydney (UTS) for providing me the International Research Scholarship.

During my research, many professional researchers and representatives of local councils and water authorities helped me produce the empirical contents of this study. Particularly, I appreciate the valuable comments and supports from Prof. Xiaochang Wang at Xi'an University of Architecture and Technology, China. I also acknowledge the strong supports to my field trials and survey from Andrzej Listowski (Sydney Olympic Park Authority), Clayton Miechel (Port Macquarie Hastings-Council) and Nigel Cosby (City West Water) as well as useful collaboration of Kelly O'Halloran (Gold Coast Water).

My thanks also are due to Dr. Thi Thu Nga Pham, Mr. Johir Mohammed and Ms. Katie McBean for their assistance throughout my experimental set-up, operation and analyses. Special thanks are to the academic and administration staff from the Faculty of Engineering and Information Technology (FEIT) and graduate research school. During my years at UTS, I was fortunate to meet many excellent fellow postgraduate students in our sustainable water research group, including Andrzej, Wen, Cong, Thanh, Bandita,

Anwar, Zuthi, Yunlong, Lijuan, Hang, Atefeh, Cheng and Van-son who shared their research interests and experience with me, and helped to make my PhD life unforgettable.

Finally, the greatest thanks must be given to my parents, who are the most ardent supporters of my studies. They are my source of wisdom and strength of mind in life. They also bring me endless energy, motivation and confidence to tackle whatever lies ahead of me. Without their unconditional love, care, patience, support and encouragement throughout my life, this lifetime milestone would not have been achieved. I dedicate this dissertation to them. I would also like to thank my relatives and friends for their generous love, support and help during the whole period of my study.

Thank you to all of you!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

AAS	atomic adsorption spectrophotometer
ABS	absorbents
AC	activated carbon
ADWG	Australia drinking water guideline
AOP	advanced oxidation process
AP	acidification potential
BC	breakthrough capacity
BOD	biochemical oxygen demand
BN	Bayesian network
BV/h	bed volumes per hour
CAS	conventional activated sludge
CBD	central business district
COD	chemical oxygen demand
COEF	coefficient
CSF	cancer slope factor
CW	constructed wetland
CWW	city west water
DAF	dissolved air flotation
DALY	disability adjusted life years
DBP	disinfection by-products
DMF	dual media filtration
DPR	direct potable reuses
ECOSAR	ecological structure activity relationship
EDCs	endocrine disrupting compounds
EDS	energy disperses X-ray spectroscopy
EIO	economic input-output
ELECTRE	elimination and choice expressing reality
EP	eutrophication potential
EPA	environmental protection agency
ERA	environmental risk assessment
ETP	ecotoxicity potential
FC	faecal coliform

GAC	granular activated carbon
GC	gas chromatography
GHG	greenhouse gas
GL	gigalitres
GL/d	gigalitres per day
GL/yr	gigalitres per year
GWP	global warming potential
GWR	groundwater replenishment
HACCP	hazard analysis critical control point
HQ	hazard quotient
HRA	health risk assessment
HRT	hydraulic retention time
ICP	inductively coupled plasma optical emission spectroscopy
ION	ion exchange
IPR	indirect potable reuses
kWh/d	kilowatt-hour per day
L	litre
LC	liquid chromatography
LCA	life cycle analysis
LCI	life cycle inventory
LCIA	life cycle impact assessment
LOAEL	lowest dose at which adverse effects are observed
L/p/d	litres per capita per day
MAUT	multi-attribute utility theory
MBR	membrane bioreactor
MCA	multi-criteria analysis
MF	microfiltration
MFA	material flow analysis
mg/g	milligram per gram
mg/L	milligram per litre
MIET	missing inventory estimation tool
ML	megalitre
ML/d	megalitres per day
ML/yr	megalitre per year

MOC	maximum operation capacity
MRA	microbial risk assessment
MS	mass spectrometry
MVC	mechanical vapour compression
NF	nanofiltration
NOAEL	highest dose at which no adverse effects are observed
NSW	New South Wales
OCWD	Orange County water district
ODP	ozone depletion potential
OR	odds ratio
ORG	organoclay
ORP	oxidation reduction potential
ORWARE	organic waste research model
PAC	powdered activated carbon
PEC	predicted environmental concentration
PHO	photochemical oxidation
PMHC	Port Macquarie-Hastings council
PNEC	predicted no effect concentration
PROMETHEE	preference ranking organization method for enrichment evaluation
QCRA	quantitative chemical risk assessment
QLD	Queensland
QMRA	quantitative microbial risk assessment
RA	risk assessment
RBC	rotating biological reactor
RC	residual chlorine
RfD	safe risk level
RHDA	Rouse Hill development area
RHWRS	Rouse Hill water recycling scheme
RIRA	recycled water irrigation risk analysis
RO	reverse osmosis
ROWG	rank order weight generation
RQ	risk quotients
RW	recycled water
RWAlterDW	recycled water is an alternative to drinking water

PhACs	pharmaceutical active compounds
SA	South Australia
SAT	soil aquifer treatment
SBR	sequencing batch reactor
SE	standard error
SEM	scanning electron microscope
SP	salinisation potential
SPSS	statistical package for the social sciences
STP	sewage treatment plant
SWC	Sydney Water corporation
TC	total coliform
TDS	total dissolved solids
TN	total nitrogen
TOC	total organic carbon
TP	total phosphorus
TSS	total suspended solids
UF	ultrafiltration
UV	ultraviolet
VIC	Victoria
VOC	volatile organic compounds
WCRWP	Western Corridor recycled water project
WHO	world health organization
WM	washing machines
WRAMS	water reclamation and management scheme
WRP	water reclamation plant
WSP	waste stabilization pond
WWTP	wastewater treatment plant

RESEARCH OUTCOMES

(9 journal papers, 4 conference papers and 7 research awards)

Journal Articles

1. **Chen, Z.**, Ngo, H. H., Guo, W. S., Pham, T. T. N., Lim, R., Wang, X. C., et al. (2014). A new optional recycled water pre-treatment system prior to use in the household laundry. *Science of the Total Environment*, 476, 513-521.

2. **Chen, Z.**, Ngo, H. H., Guo, W. S., Lim, R., Wang, X. C., O' Halloran, K., et al. (2014). A comprehensive framework for the assessment of new end uses in recycled water schemes. *Science of the Total Environment*, 470-471, 44-52.

3. **Chen, Z.**, Ngo, H. H., Guo, W. S., Wang, X. C., Miechel, C., Corby, N., et al. (2013). Analysis of social attitude to the new end use of recycled water for household laundry by the regression models. *Journal of Environmental Management*, 126, 79-84.

4. **Chen, Z.**, Ngo, H. H. and Guo, W. S. (2013). Risk control in recycled water schemes. *Critical reviews in Environmental Science and Technology*, 43(22), 2439-2510.

5. **Chen, Z.**, Ngo, H. H. and Guo, W. S. (2013). A critical review on the end uses of recycled water. *Critical reviews in Environmental Science and Technology*, 43(14), 1446-1516.

6. **Chen, Z.**, Ngo, H. H., Guo, W. S. and Wang, X. C. (2013). Analysis of Sydney's recycled water schemes. *Frontiers of Environmental Science and Engineering,* 7(4), 608-615.

7. **Chen Z.**, Ngo H. H., Guo W. S., Listowski, A., O'Halloran, K., Thompson, M., et al. (2012). Multi-criteria analysis towards the new end use of recycled water for

household laundry: A case study in Sydney. *Science of the Total Environment*, 438(1), 59-65.

8. **Chen, Z.**, Ngo, H. H. and Guo, W. S. (2012). A critical review on sustainability assessment of recycled water schemes. *Science of the Total Environment*, 426(1), 13-31.

9. **Chen, Z.**, Ngo, H. H., Guo, W. S., Wang, X. C. and Luo, L. (2011). Probabilistic risk assessment of recycled water schemes in Australia using MATLAB toolbox. *Journal of Water Sustainability*, 1(3), 75-86.

Conference Papers

1. **Chen, Z.**, Ngo, H. H., Guo, W. S. (2013). Conceptual principle for development of new end uses in recycled water schemes. Proceedings of the 4th International Symposium "Re-Water Braunschweig", November 6-7, 2013, Braunschweig, Germany. p. 27-34.

2. **Chen, Z.**, Ngo, H. H., Guo, W. S., Listowski, A., O' Halloran, K., Thompson, M. and Muthukaruppan, M. (2012). Multi-criteria analysis of Sydney's recycled water schemes towards the new end use for washing machines, Poster presentation, *IWA World Water Congress and Exhibition*, Busan, Korea, 16-21 September, 2012.

3. **Chen Z.**, Ngo H. H., Guo W. S. and Wang X. C. (2011). Analysis of Sydney's recycled water schemes. Oral presentation at the IWA Conference-*Cities of the Future Xi'an: Technologies for integrated urban water management*, China, 15-19 September, 2011.

4. **Chen, Z.**, Ngo, H. H., Guo, W. S., Wang, X. C. and Luo, L. (2011). Probabilistic risk assessment of recycled water schemes in Australia using MATLAB toolbox. Oral presentation at the *International Conference on Challenges in Environmental Science and Engineering (CESE)*, Tainan, Taiwan, 25-30 September, 2011.

Research awards

1. Excellence in Professional Development Program in Civil & Environmental Engineering Research, CTWW, UTS 07/2011−12/2013

2. Finalist at the 2013 UTS final 3 Minutes Thesis Competition 08/2013

3. Best oral presentation award at the UTS Faculty of Engineering and Information Technology (FEIT) 3 Minutes Thesis Competition 08/2013

4. Best oral presentation award at the UTS FEIT Research Showcase Contest 06/2013

5. Best poster presentation award at the International Water Association (IWA) World Water Congress and Exhibition, Busan, Korea, 16-21 September, 2012 09/2012

6. Best student oral presentation award at the International Conference on Challenges in Environment Science & Engineering, Taiwan, 25-30 September, 2011 09/2011

7. University of Technology, Sydney (UTS) International Research Scholarship 01/2011−12/2013

ABSTRACT

Nowadays, recycled water has provided sufficient flexibility to satisfy short-term freshwater needs and increase the reliability of long-term water supplies in many water scarce areas. It becomes an essential component of integrated water resources management. However, the current applications of recycled water are still quite limited with non-potable purposes such as irrigation, industrial uses, toilet flushing, car washing and environmental flows. There is a potential to exploit and develop new end uses of recycled water in both urban and rural areas. This can contribute largely to freshwater savings, wastewater reduction and water sustainability.

This thesis put forwards a conceptual decision making framework for the systematic feasibility assessment of sustainable water management strategies in related to new end uses of recycled water's planning, establishment and implementation. Due to the transparency, objectivity and comprehensiveness, the analytic framework can facilitate the optional management strategy selection process within a larger context of the community, processes, and models in recycled water decision-making. Based on that, a simplified quantitative Multi-criteria Analysis (MCA) was conducted in Rouse Hill Development Area (RHDA), Sydney, Australia, using the Multi-attribute Utility Theory (MAUT) technique. The results indicated that recycled water for a household laundry was the optimum solution which best satisfied the overall evaluation criteria. Another two management options can be excluded from further consideration in initial stages, namely the implementation of Level 1 water restriction on the use of recycled water and recycled water for swimming pools.

With the identified strengths of recycled water use in washing machines, five relevant management alternatives were proposed according to different recycled water treatment technologies such as microfiltration (MF), granular activated carbon (GAC) or reverse osmosis (RO), and types of washing machines (WMs). Accordingly, a comprehensive quantitative assessment on the trade-off among a variety of issues (e.g., technical, risk, social, environmental and economic aspects) was performed over the alternatives. Overall, the MF treated recycled water coupled with new washing machines and the MF-GAC treated recycled water coupled with existing washing machines were shown

to be preferred options. The results could provide a powerful guidance for sustainable water reuse in the long term. However, more detailed field trials and investigations are still needed to understand, predict and manage the impact of selected recycled water new end use alternatives effectively.

Notably, public acceptability becomes important to ensure the successful development of recycled water new application in household laundries. This thesis addresses social issues by extensive social attitude surveys conducted in three locations of Australia, namely Port Macquarie, Melbourne and Sydney. Based on responses from Port Macquarie and Melbourne, the regression models provide conclusions about which characteristics are more likely to lead to the acceptance of recycled water from society. Three attitudinal variables (i.e., recycled water is an alternative to drinking water, attitude and cost) and three psychological variables (i.e., odour, reading and a small treatment unit) were found to be the key driving forces behind domestic water reuse behaviour. Comparatively, survey results in Sydney indicated slightly different aspects of concern. Due to experience in current use on dual pipe systems, Sydney residents interviewed have established good cognitions on the appearance and cost of recycled water. They were more concerned about the colour of clothes and potential damage to washing machines. The overall findings could drive future research to achieve a better public perception of the new end uses of recycled water.

Moreover, the thesis also demonstrates the feasibility and cost-effectiveness of applying a zeolite filtration column as an effective ion-exchange resin for recycled water softening prior to use in washing machines. At the laboratory scale, the column service life for a typical washing machine was approximately one month without material regeneration on the basis of an optimal contact time (i.e., 5 minutes) and the calculated breakthrough capacity (i.e., 14 milligram hardness ions per gram of zeolites). It is believed that with a full application at households, this unit is likely to play a positive role in guaranteeing the recycled water quality as well as changing the public perception on the safe use of recycled water.